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The simulation model of flux density distribution on an absorber tube

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Abstract

A parabolic trough collector (PTC) is an important component of parabolic trough solar thermal power generation system. The main purposes of calculating the flux density distribution are as follows: (1) the heat flux distribution on the absorber tube surface is a key boundary condition in the heat transfer performance analysis; (2) it can present a reference for design and optimization of PTCs, and make PTCs more cost effective. In this paper, coordinate transformations and Monte Carlo Ray Trace (MCRT) method are combined to simulate the circumferential flux distribution of absorber tubes. In the simulation process, non-parallelism of solar rays with cone optics, geometric concentrating ratio (GC), rim angle, transmittance of the glass tube, absorption of the absorber tube, reflectivity of the glass tube and reflectivity of the parabolic trough mirror are considered. The results show good agreement with references.

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Keywords: parabolic trough collector; MCRT; flux density distribution

1. Introduction

Since the 1970s, more and more attention has been paid to the research of renewable energy resources due to the increasing energy demand and the environmental pollution of burning fossil fuel. It is well known that solar energy is clean, pollution-free, sustainable and the most widely and largest distributed renewable energy resource available on the earth, and thus has broad application prospects. Concentrating solar power (CSP) technologies are promising and gaining increasing attention. Recently, CSP technologies have experienced revived market growth. Across all the CSP technologies, the parabolic trough solar thermal power (PTSTP) generation technology is the most widely-

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applied solar thermal power generation technology. About 90% of commercial CSP plants are parabolic trough technology, including the SEGS plants in the California and the 100MWe solar power plant in Abu Dhabi.

A PTC concentrates the incident rays at its focal line. PTCs typically account for 30% of the cost of the parabolic trough plants. Many significant experiments and simulations of PTCs have been published. In 1977, D.L.Evans used "cone optics" to establish the cylindrical parabolic solar concentrators with flat absorbers, considering the influence of the finite size of sun[1]. A first integral of the concentrated energy flux distribution by a semifinite formulation was developed, considering various incident angles[2]. A.Thomas and Halil M.Guven considered effect of optical errors of PTCs, and gave in depth information about the flux distribution for various optical errors and geometry[3]. Ya-Ling He[4]and Z.D.Cheng[5]calculated flux distribution in ideal conditions by the Monte Carlo Ray Trace (MCRT) method. Zhiyong Wu[6]used FLUENT to establish the flux distribution on the absorber tube and analyze temperature distributions at the joint position of absorbers.

In this paper, coordinate transformation (CT) is used to calculate the circumferential flux distribution, which can accurately find the reflected ray position on absorber tubes corresponding to the incident light. Non-parallelism of solar rays with cone optics, transmittance of the glass tube, GC, rim angle, absorption of the absorber tube and reflectivity of the reflector are considered.

2. Analytical expressions

Parabolic trough technology uses reflectors to collect parallel rays and nearly parallel rays from the solar beam into a line image. A long pipe receiver is placed at the focus line for heating the heat transfer fluid (HTF). It is important to improve parabolic trough concentrators, in order to reduce the cost of parabolic trough plants.

The key considerations for calculating circumferential flux distribution include the following:

- Every ray has the same energy;
- The displacement of refracted rays due to glass cover is ignored;
- The reflected rays by the absorber tube are not considered regarding whether it heats the absorber again;

The coordinate system used in this paper is Cartesian coordinates, which is built according to the left hand rule, and the range of absorber tube circle angle ξ is from -180°to 180°, as shown in Fig.1(a). The flowchart for coordinate transformations combined with MCRT is shown in Fig.2. The radial angle θ and circumferential angle ψ of incident rays in the beam cone have been derived.

$$\begin{aligned} &\theta = \tan^{-1}\left(\sqrt{\varepsilon_1}\tan\theta_{\max}\right) \\ &\psi = 2\pi\varepsilon_2 \end{aligned} \tag{1}$$

Here, ε_1 and ε_2 are random numbers between 0 and 1. $\theta_{\max}$ =4.65mrad is used to represent the finite size of the sun. The schematic diagram of incidence ray vector O_0P_1 is shown in Fig.1(b).

Incidence ray vector O_0P_1 at coordinate system O_0XYZ is described and the coordinate value of O_0 is $O_0 = (x_0, y_0, z_0)^T$ at $OXYZ$.

$$O_0P_1 = \left(\sin\theta\cos\psi, \cos\theta, \sin\theta\sin\psi\right)^T \tag{2}$$

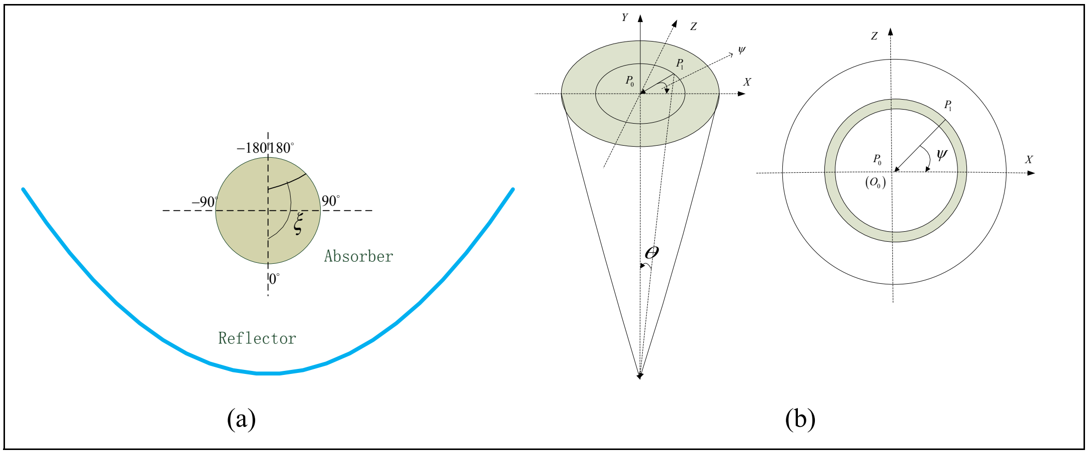

Fig. 1. (a)The range of absorber tube circle angle ξ ; (b) incidence ray vector O_0P_1 .

In order to calculate the reflected ray O_0P_3 at $OXYZ$, coordinate transformations is used. The projection vector of central incident ray O_0P_0 at α projection plane is $O_0N_0 = (0,1,0)^T$, and the same to central reflected ray O_0P_2 is O_0N_2 .As the parabolic equation is $X^2 = 4fY$, the normal vector at point O_0 to the inner parabolic surface is $O_0N = (-x_0, 2f, 0)^T$. χ is the angle between O_0N_0 and O_0N_2 , which is shown in Fig.3(a).

$$\chi = 2\cos^{-1}\left(\frac{O_0N \cdot O_0N_0}{|O_0N||O_0N_0|}\right) \tag{3}$$

In order to calculate reflected ray, coordinate system $O_0X_2Y_2Z_2$ is built. O_0N_2 is the Y_2 -axis, and O_0P_4 is the Z_2 -axis, which is parallel to Z -axis. X_2 -axis is built according to left-half rule defined as O_0N_3 . The reflected ray is O_0P_3' in $O_0X_2Y_2Z_2$ and O_0P_3 in O_0XYZ . The relationship of O_0XYZ and $O_0X_2Y_2Z_2$ is shown in Fig.3(b). O_0P_3 and O_0P_3' is expressed as follows. The relationship O_0P_3 and α is shown in Fig.4.

$$O_0P_3 = A \cdot O_0P_3' = (x_3, y_3, z_3)^T \tag{4}$$

$$A = \begin{bmatrix} \cos\chi & -\sin\chi & 0 \\ \sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

A is the coordinate transformation matrix between O_0XYZ and $O_0X_2Y_2Z_2$.

According to symmetry, the relationship of incident ray O_0P_1 and reflected ray O_0P_3' is shown in Fig.5. The expression of O_0P_3' in $O_0X_2Y_2Z_2$ is expressed.

$$O_0P_3' = (-\sin\theta\cos\psi, \cos\theta, -\sin\theta\sin\psi)^T \tag{6}$$

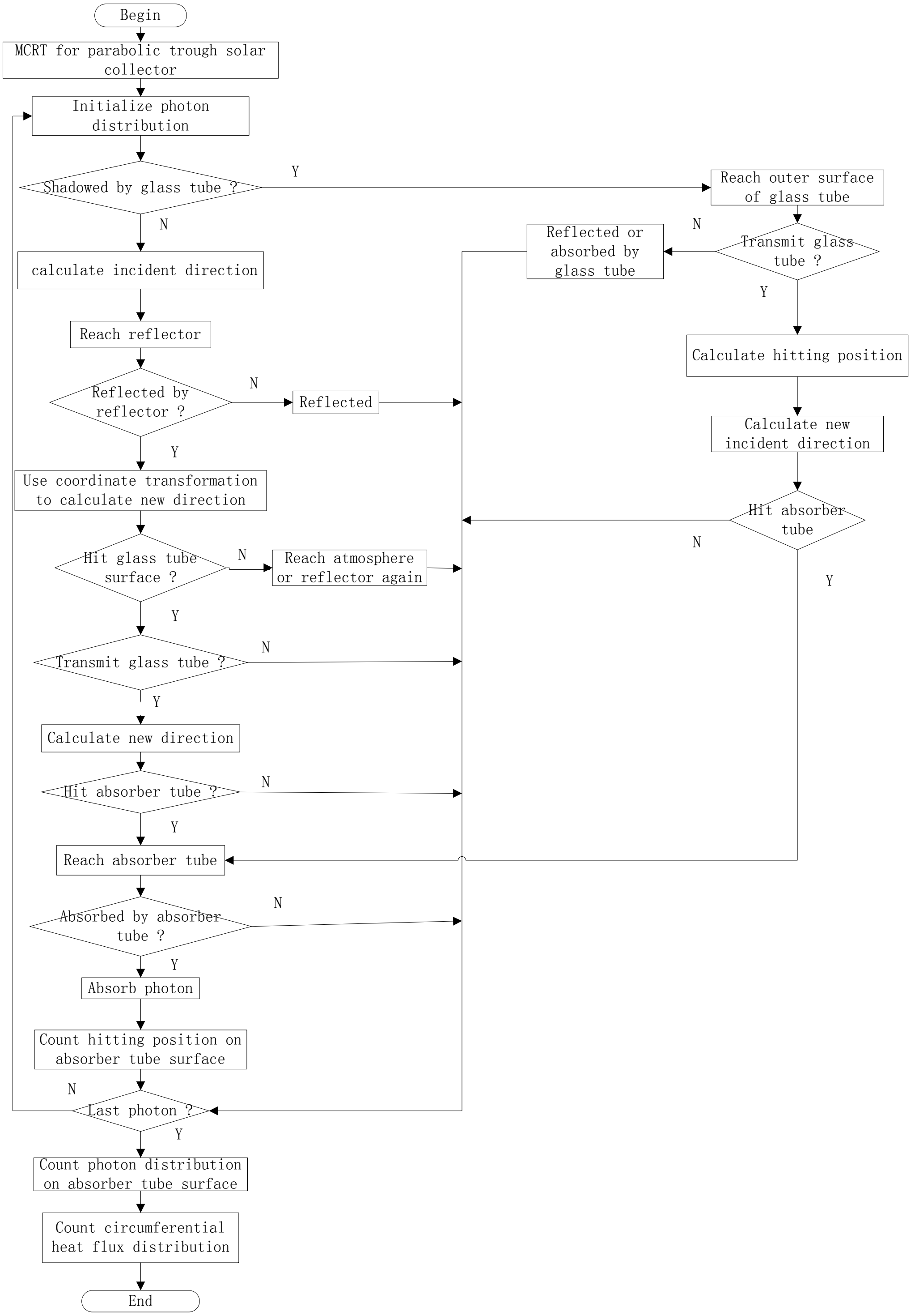

Fig. 2.The flowchart for coordinate transformations combined with MCRT

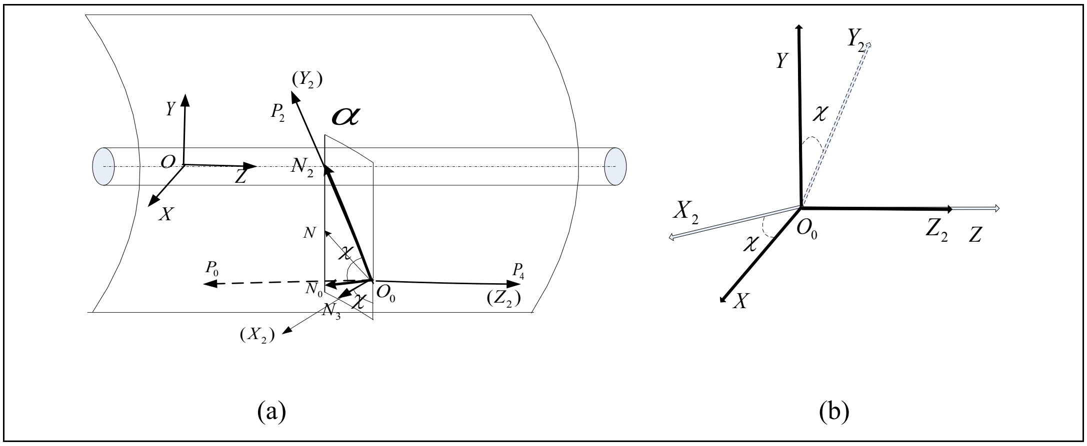

Fig. 3.The reflected ray and the coordinate transformation of reflected ray

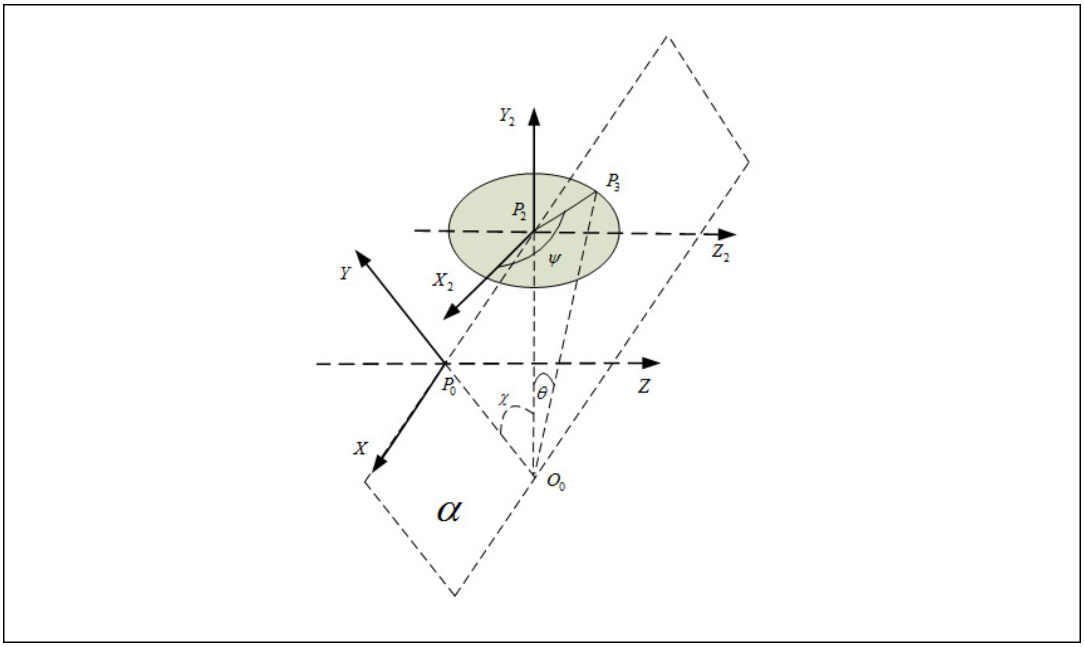

Fig. 4.The relationship of O_0P_3 and α

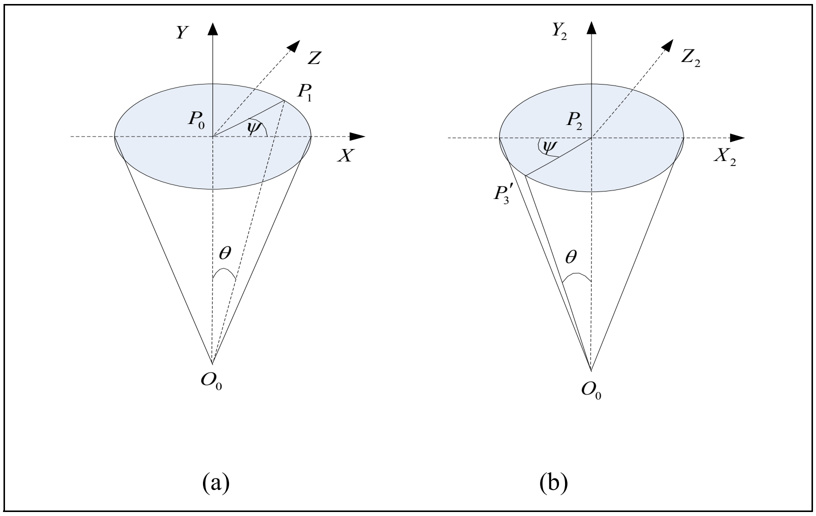

Fig. 5.The relationship of incident ray O_0P_1 and reflected ray O_0P_3'

The reflected ray O_0P_3 hits outer surface of the glass tube at point $G_1=(x_{G1},y_{G1},z_{G1})^T$. And equations of the reflected ray and outer surface of the glass tube are expressed. Equations (7) and (8) can be solved simultaneously to calculate $G_1=(x_{G1},y_{G1},z_{G1})^T$.

$$\frac{X-x_0}{x_3}=\frac{Y-y_0}{y_3}=\frac{Z-z_0}{z_3} \tag{7}$$

$$X^2+(Y-f)^2=R_2^2 \tag{8}$$

Where R_2 is the radius of outer glass tube.

When reflected rays transmit glass tube, the displacement can be ignored in glass tube. The reflected ray hits absorber tube at point $G_2=(x_{G2},y_{G2},z_{G2})^T$ .And G_2 is $G_2=(R_2,\delta,z_{G2})^T$ in cylindrical-coordinate system. The equation of absorber tube is described. And (7) and (9) can be used to calculate $G_2=(x_{G2},y_{G2},z_{G2})^T$.

$$X^2+(Y-f)^2=R_1^2 \tag{9}$$

Where R_1 is the radius of outer absorber tube, and δ is the angle of the hitting position on the absorber tube.

3. Simulation results and verification

In order to verify the accuracy of the simulation method, the simulation results were compared with S.M.Jeter's[5] , with the parameters of the simulation model the same as Jeter's, as shown in Table 1, noting that solar radius is 7.5mrad. The results are shown in Fig.5. The width of the aperture is W , and GC is specified as follows.

$$GC=\frac{W}{2\pi r_2} \tag{10}$$

Table 1: Parameters of simulation model

Parameter	Value
geometric concentrating ratio(GC)	20.00
rim angle(θ_{rim})	90°
transmittance of glass tube(τ)	1.00
absorption of absorber tube(α)	1.00
reflectivity of parabolic trough mirror(ε)	1.00
reflectivity of glass tube(υ)	0.00
radius of absorber tube(r_a)	0.035m
Angular radius of sun (mrad)	7.5

In Fig.6, the simulation results in this paper show that the distribution matches very well with Jeter's results. The greatest difference is at ξ =0°, which is 6.30%, and the other results are similar to Jeter's. It verifies that the method is reliable in this paper. The flux density distribution can be divided into four regions, the shelter region [1], the incremental region [2], the attenuation region [3] and the direct radiation region [4]. In part [1], the flux density is low, but increases very rapidly, because the radiation is shadowed by the absorber. In part [2], it increases to the maximum value, because more and more rays are reflected to the absorber. In part [3], the flux density reduces very rapidly, because reflected rays decrease. In part [4], few rays are reflected to the absorber, and it only gets the direct radiation.

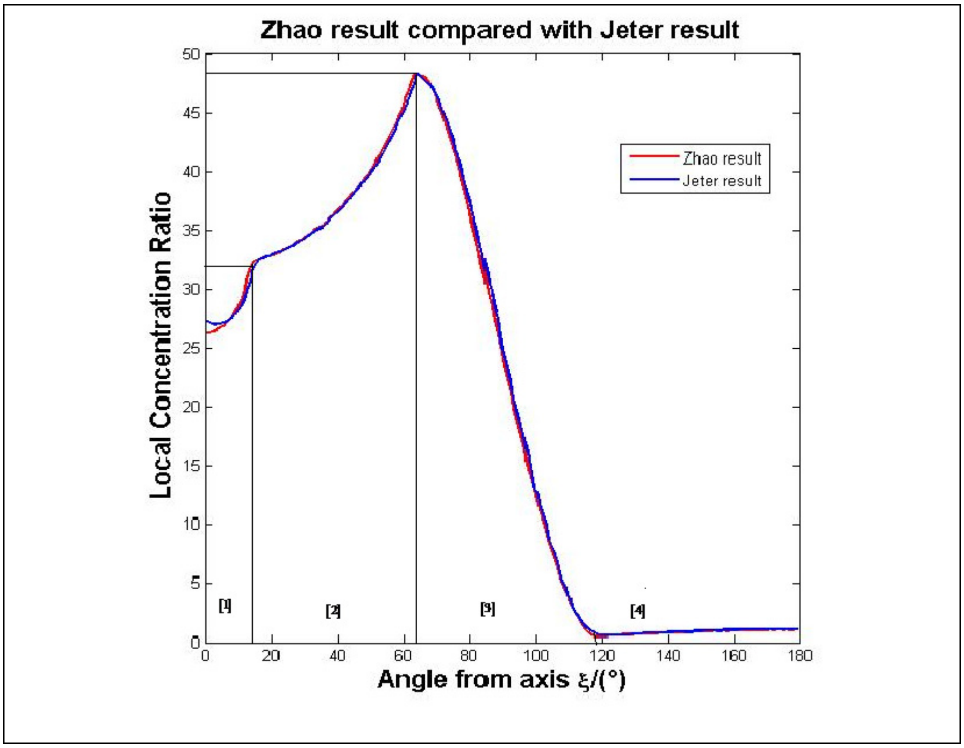

Fig.6.The flux density distribution considering a round receiver, GC=20, rim angle=90°, 7.5mrad angular radius and incident angle=0°

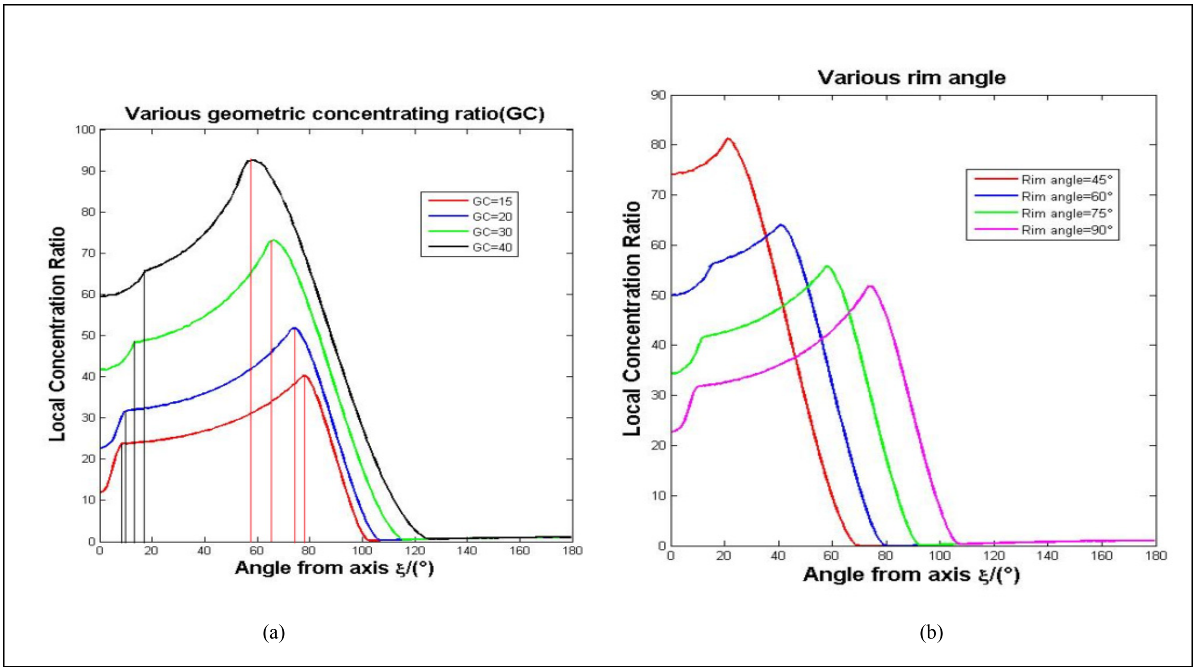

Fig.7. The flux density distribution considering different GCs(a) and various rim angles(b) considering a round receiver, 4.65mrad angular radius and incident angle=0°

In this method, a solar radius of 4.65mrad is considered. Except for different solar radius, other parameters are same as Table 1.

While the rim angle is 90°, and solar radius is 4.65mrad, the flux density distribution varies with different GCs, which is shown in Fig.7(a). As GCs rise, local concentration ratio increases rapidly, especially the maximum value, and the relative ξ angle of the maximum value decreases.

Fig.7(b) shows the flux density distribution on the absorber tube under different rim angles, when GC is 20, and solar radius is 4.65mrad. As rim angles change from 45°,60°,75°to 90°, the maximum flux becomes lower, and the trend of flux distribution curve becomes smoother.

4. Conclusion

As illustrated above, non-parallelism of solar rays with a 9.3mrad optics cone, transmittance of the glass tube, GC, rim angle, absorption of the absorber tube and reflectivity of the reflector are considered. The Coordinate transformation method is used to accurately simulate the reflected ray position on the absorber and calculate the flux density distribution with different GCs and rim angles. The simulation results show this method is very reliable compared with reference results.

In this paper, the simulation results can be used to evaluate the optical performance of PTCs, provide a reference for design and optimization PTCs, and furnish boundary condition of the absorber tube in the heat transfer performance analysis

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